Progress report for the period 1 January to 31 December, 1953

on

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between

The Office of Naval Research (Biology Branch), U. S. Navy

and

The Bingham Oceanographic Laboratory, Yale University

Annual rate $8000.

Title: Oceanographic survey of the central and eastern parts of Long Island Sound.

Report prepared by:

Gordon A. Riley

28 January, 1954

Personnel and their individual tasks are as follows:

Principal investigator: Gordon A. Riley - Physical and chemical oceanography.

Assistant: Shirley M. Conover - Phytoplankton; technical assistance in physical and chemical oceanography.

Associated members of the Bingham staff:

Georgiana B. Deevey - Zooplankton (on leave of absence July, 1953 to June, 1954).

Sarah B. Wheatland - Fish eggs and larvae.

Part-time undergraduate assistants:

Louis Mowbray, Francisco Wong, Samuel Andreades - technical assistance to other members of the project.

Graduate students:

Robert J. Conover - Biology of the copepod Acartia.

Howard Sanders - Bottom fauna.

Eugene Harris - The nitrogen cycle.

Two first year graduate students have asked to be admitted to the project for thesis research. Theodore Napora is interested primarily in zooplankton, Salah El Zarka in fishes. Definite research topics have not been chosen.

Material has been collected for two associates in the university. One is working on the taxonomy of nematodes, the other on pigments, vitamins, and vitamin precursors in plankton.

From time to time Luigi Provasoli of the Haskins Institute in New York has given us excellent help and advice in experimental studies of the nutrient requirements of phytoplankton. Recently he has undertaken to isolate and make laboratory studies of some of the dominant species of the Long Island Sound flora. A comparative study of the behavior of these species in culture and in nature is certain to be rewarding, and we are fortunate to have the help of one of the world's foremost students of algal nutrition.

Objectives:

(1) To obtain detailed information on the species composition, abundance, and seasonal cycles of the Long Island Sound fauna and flora and on the physical and chemical nature of the environment.

(2) To determine insofar as possible the sources and rates of supply of essential inorganic elements and to measure the productivity of major ecological groups of organisms.

(3) To analyse population abundance and productivity with respect to climatic, geographical, and internal biological factors.

Summary of results and immediate plans for the future.

We have completed 22 months of weekly observations in the central part of Long Island Sound, consisting of temperature, salinity, transparency of the water, phosphate, nitrate, oxygen, chlorophyll content of the phytoplankton, and collections of phytoplankton and zooplankton. We are essentially up to date in processing routine observations and entering them in data files and punch cards. However, the zooplankton counts have fallen behind during Dr. Deevey's absence, and Miss Wheatland, who came in after the project started, has not yet caught up.

Thus far the second year has been fairly similar to the first with respect to seasonal cycles of physical and chemical properties and plankton. Minor differences in phytoplankton and nutrient cycles are clearly correlated with meteorological factors. The summer zooplankton crop in 1953 was considerably smaller than in 1952, and in this case the reasons are not apparent in preliminary analysis.

In any oceanographic survey it is desirable to continue the observations long enough not only to establish a typical, average picture but also to analyze year-to-year fluctuations in the populations in relation to basic environmental factors. However, the law of diminishing returns begins to operate very quickly in a detailed survey. Each year there is less new information to be extracted from the data,

With the conclusion of the first two years' work in March, I believe we shall reach this point of diminishing returns. If we reduce the survey at that time to perhaps two stations at biweekly intervals, there will be some blurring of minor details, but any major year-to-year fluctuations will be clearly evident. Reducing the local survey will also enable us to spend a correspondingly larger part of our time on other problems that have not yet received adequate attention.

In January, 1953, we undertook a series of mass collections of plankton for chemical analysis and a study of the photosynthesis, growth, and nutrient requirements of phytoplankton. Preliminary results were described in the third semiannual report. This is the most important part of the investigation of basic productivity in Long Island Sound, and it will be continued, with some modifications and elaborations throughout the period of the contract.

Current measurements obtained during the present survey have been combined with previous studies by the Coast and Geodetic Survey. Analysis of the data leads to a consistent picture of water exchange within Long Island Sound and between the Sound and adjacent waters during the summer season. Results are presented in Appendix A.

Appendix B analyzes the first eithteen months' data on water transparency. Transparency is one of the most important factors governing productivity, since it sets a limit on the depth range of effective phytoplankton photosynthesis. The appended material is the first attempt that has been made to assess quantitatively the factors controlling transparency in coastal waters. The results are preliminary, not altogether satisfactory, and are likely to be revised when more data become available. However, it is encouraging that some progress has been made, with relatively little effort, in a subject that is fundamentally quite complex.

Robert Conover has obtained a series of collections of the copepod Acartia designed to determine their vertical distribution and seasonal growth pulses. He has performed extensive laboratory experiments on respiration and feeding rates. He can reasonably expect to have enough data for a doctoral thesis within the next six months.

After preliminary exploration of various techniques, Howard Sanders has adopted a program of bottom fauna collections at six-week intervals with a coring tube and a bottom dredge of new design. Field work will continue for another 8 - 12 months. He hopes to present his dissertation in the spring of 1955.

Eugene Harris also has had a long preliminary period of experimenting with methods, since seawater analyses of the various forms of combined nitrogen leave much to be desired. During a summer fellowship at the Woods Hole Oceanographic Institution he worked on methods and in August joined a cruise to the Sargasso Sea. Samples were obtained from a variety of inshore and offshore locations. These will be useful for comparison with Long Island Sound. He is currently working again on methods and will shortly be ready to start a full-scale survey.

Long range plans.

In March, 1954, we propose to initiate a two-year program of approximately monthly cruises covering most or all of Long Island Sound and designed to investigate the following points:

(1) Description of seasonal cycles in the Sound as a whole, their local variations, and the effects of such variations on other areas due to water transport.

(2) An analysis of monthly variations in transport exchange by the salt continuity principle. Having established in Appendix A an average pattern of summer circulation, we are ready to undertake the further problem of determining its seasonal perturbations. Direct observation by current measurements would require an expensive program with automatic recording devices or a still more expensive multiple ship operation. However, salinity observations and data on freshwater drainage will provide an estimate of total salt flux, which is in some respects better for biological purposes than simple current measurements.

(3) Measurement of total nitrogen (Harris) and phosphorus (senior investigator) and their component fractions in Long Island Sound waters and the freshwater drainage system. Combined with (2) above, these will yield estimates of both the internal biological cycles of the two elements and the exchange due to water movements.

After the conclusion of this program, which coincides with the termination of the present contract, I expect to continue working in Long Island Sound. The exact nature and extent of the work will depend on unforeseen factors, principally how much is accomplished in the next two years and how many graduate students are working with me.

Certain broad oceanographic aims can be accomplished only by a long-term program:

(1) In the few areas where observations have continued for ten years or

more, long period trends have proved to be not only a valuable tool in oceanographic analysis but also important practically in evaluating fluctuations in commercially valuable species.

(2) I have been interested for some years in quantitative ecological theory. This theory says in essence that about half a dozen basic climatic and geographical factors determine what organisms can exist in a given region and control population size through their influenne on the rates of various physiological processes. If these processes can be described in ecological terms with sufficient accuracy, it is then possible to set up a series of mathematical equations to predict seasonal and long period population trends in terms of relatively simple climatic fluctuations.

Considerable progress has been made in the theory of oceanic populations Coastal waters are more difficult. The nutrient supply depends upon freshwater drainage and a complicated transport system rather than simple vertical exchange. Proximity to land strongly influences the transparency of the water. The existence of a large bottom fauna with diverse and specialized habits introduces great complications into the biological treatment. These difficulties intensify sceintific interest in the subject, with the additional consideration that it is in shallow water, where the commercial fisheries are concentrated, that a theoretical prediction scheme is most likely to pay practical dividends. On the other hand, it is such a difficult problem that I shall not wholly commit myself to it unless the results of the present survey indicate considerable liklihood of eventual success.

Reports and publications.

Preliminary accounts of the project were presented by the senior investigator and the Conovers at the annual meeting of the American Society of

Limnology and Oceanography at Madison, Wisconsin in September.

Mrs. Conover's study of red tides in New Haven Harbor (Appendix B, third semiannual report) has been accepted for publication in the Journal of Marine Research.

General plans for publication include the following:

(1) A series of papers covering essentially the first two years' work and primarily concerned with the central part of Long Island Sound. Papers by Riley on physical and chemical oceanography, Shirley Conover on phytoplankton, and Robert Conover on his thesis research are expected to go to press toward the end of 1954 and probably will be published under a single cover as an issue of the Bulletin of the Bingham Oceanographic Collections. Papers by Deevey and Wheatland will be included if they are finished in time. Sanders' work will hot be ready until the following year.

(2) A second and similar series covering the work of 1954-5.

(3) Interim reports. Most of the work of the survey is so closely interconnected that the results are best published in series for ready comparison of one phase with another. Occasionally special and relatively isolated tasks are undertaken, such as the red tide investigation and the synoptic model of the Sound. Such material will be published as soon as possible after completion of the task.

Since oceanographic surveys require a relatively long period of data collection before a complete account can be written, I have adopted a policy of submitting detailed but preliminary reports of certain phases of the work as appendices to the progress reports. These are subject to revision when more data come in; otherwise they serve the function of technical reports in presenting a formal treatment of scientific results.

APPENDIX A. Water exchange in Long Island Sound.

Various aspects of the Long Island Sound circulation have been discussed in previous reports and particularly in Appendix A of the third semiannual report. Direct current observations have confirmed the existence of a two-layered transport system, in which a surface layer flows eastward toward the open sea and is replaced by a westward inflow along the bottom. This exchange is large enough to be an important factor influencing the biological productivity of the Sound. It enriches the Sound with phosphate and other essential plant nutrients during the spring and summer when these nutrients are in short supply and are particularly needed to promote productivity. The mechanism of accumulation was discussed at the Madison meetings, and preliminary estimates were made of the rate of enrichment. The final account awaits the results of the next two years.

Although the transport is of primary importance in determining both physical and biological characteristics of the Sound, its actual volume is small compared with ordinary east-west tidal oscillation, and it is readily modified by winds and density currents. Our observations reveal disconcertingly large variations in residual flow from one tidal cycle to another and even larger differences between one station and the next. A detailed study of currents would require long-period observations, presumably with automatic recorders, at a considerable number of stations. Biological aims hardly warrant the necessary expenditure. Most of our purposes will be served if we can establish a reasonably consistent pattern of east-west transport at one season of the year and then determine monthly variations from that pattern by applying the principle of salt continuity.

Figure 1 shows a pattern of stations that will be used for estimating east-west transport across the lines indicated in the figure. The data were

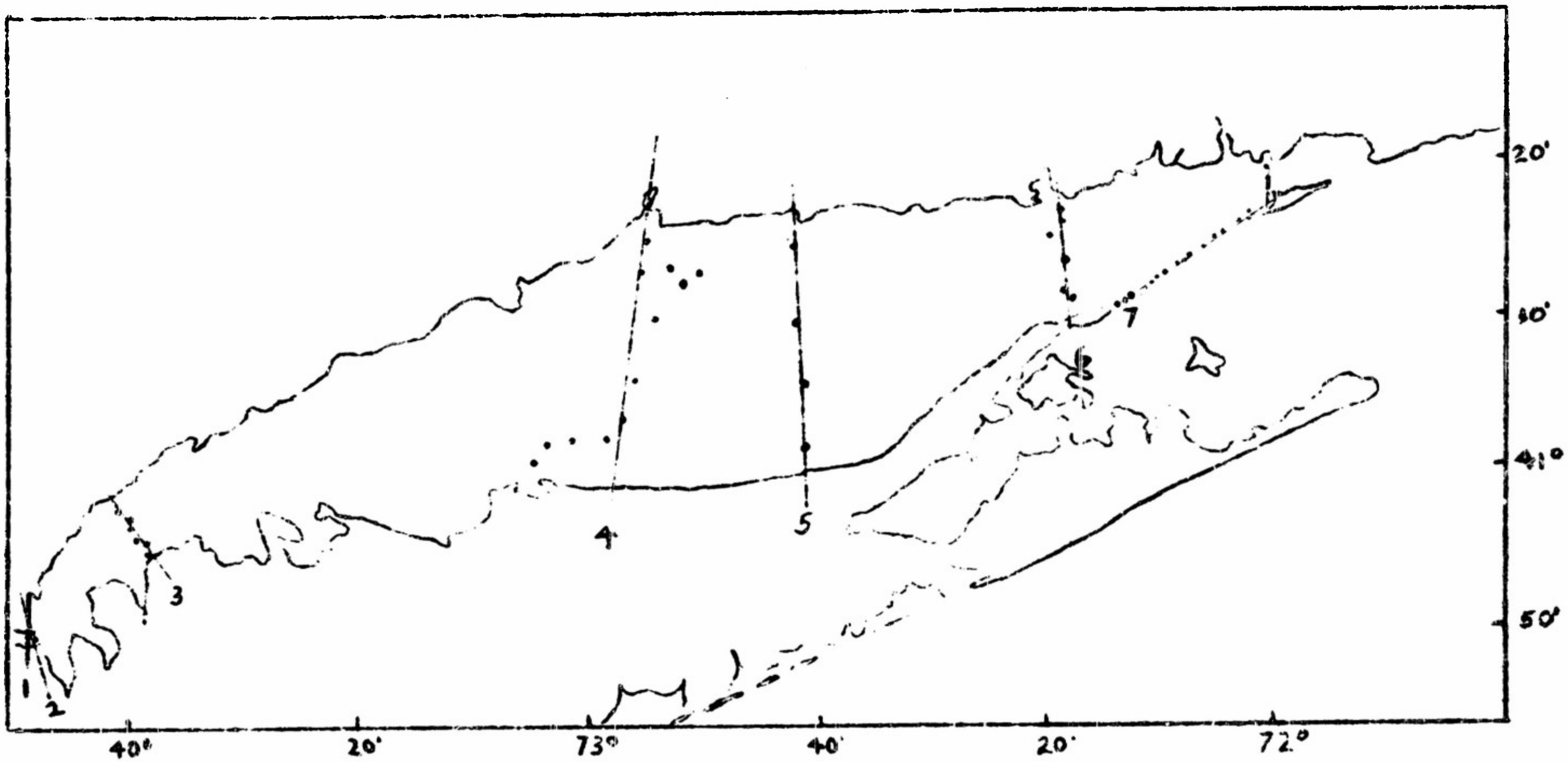


Figure 1. Positions of current stations and profiles

obtained in the summers of 1890, 1917, 1929 (Special Publication 174, U. S. Coast and Geodetic Survey) and 1953. Publication 174 lists the duration and maximum velocity of flood and ebb at the surface and usually two or three subsurface levels. Residual transport is calculated by assuming that the mean velocity is two-thirds the maximum, multiplying this figure by the duration, and taking the difference between flood and ebb. Our 1953 data, consisting of half-hourly readings at four to six depths, are numerically integrated through a complete tidal cycle. Figure 2 is a sample of the type of results obtained. The numbers show transport in nautical miles during a tidal cycle, the positive sign indicating easterly movement

The profiles provide a basis for calculating the volume transport through successive cross sections of Long Island Sound. However, the amount of variation from one depth to another and from station to station makes interpolation fairly difficult. Moreover, there is no assurance that the observed variations all represent consistent local differences. Most of the stations were occupied during one tidal cycle, and a longer period is necessary in order to rule out random fluctuations. Thus the validity of the results depends upon having enough stations to average out various errors.

With these qualifications in mind, a tentative estimate of transport for the series of profiles is presented in Table 1. The amount of bottom inflow entering the Sound at profile 7 cannot be determined because there were not enough deep water measurements. At profile 6 it is about 15 thousand m^3 per second and declines steadily to zero at the western end. Clearly this water is upwelling and augmenting the surface flow.

It would appear that about 1100 m^3/second enter the western end of the Sound and flow eastward as part of the surface layer. The latter is further

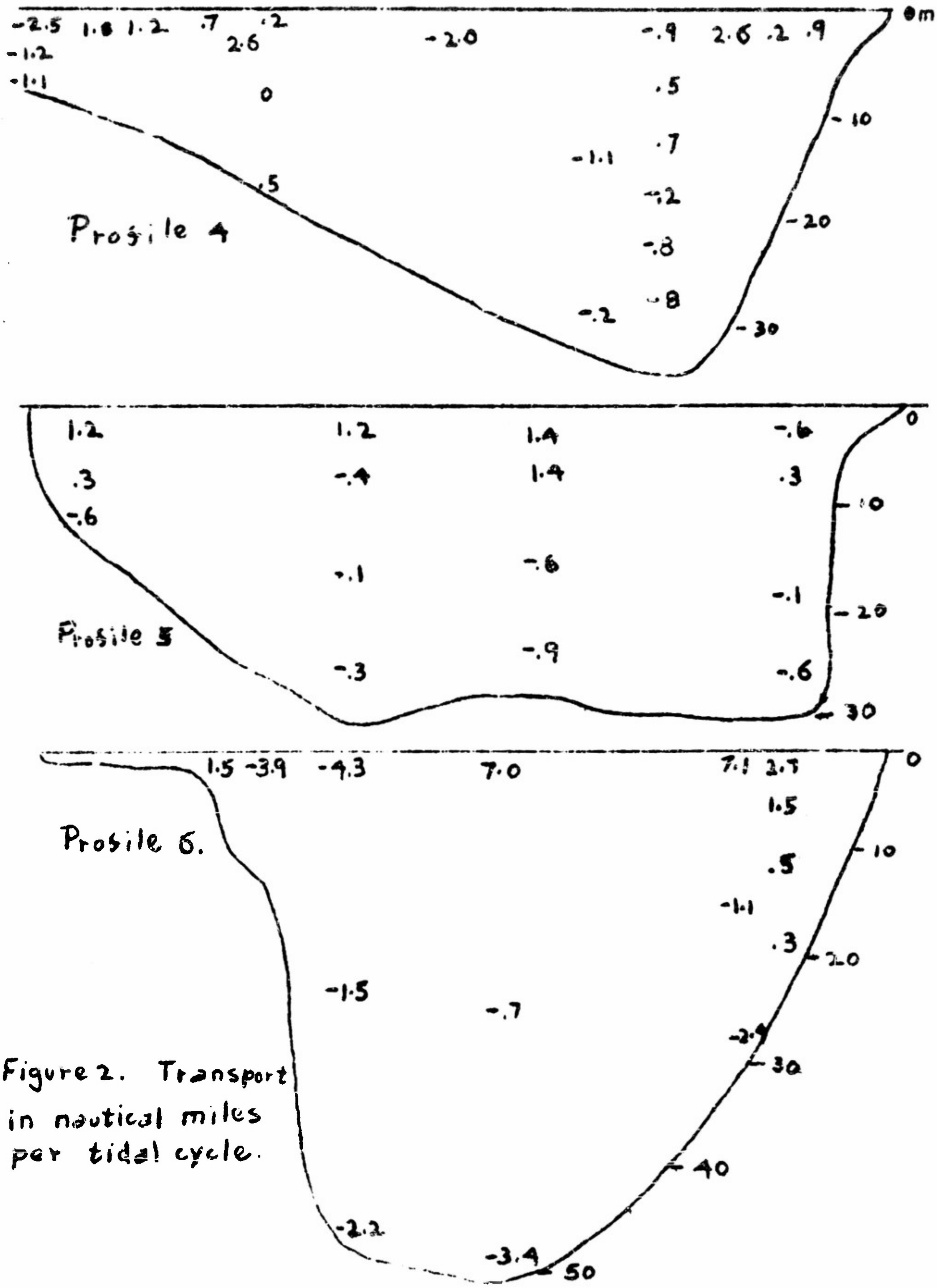


Figure 2. Transport in nautical miles per tidal cycle.

Table 1. Volume transport in m^3/second through profiles 1 to 7 (Figure 1).

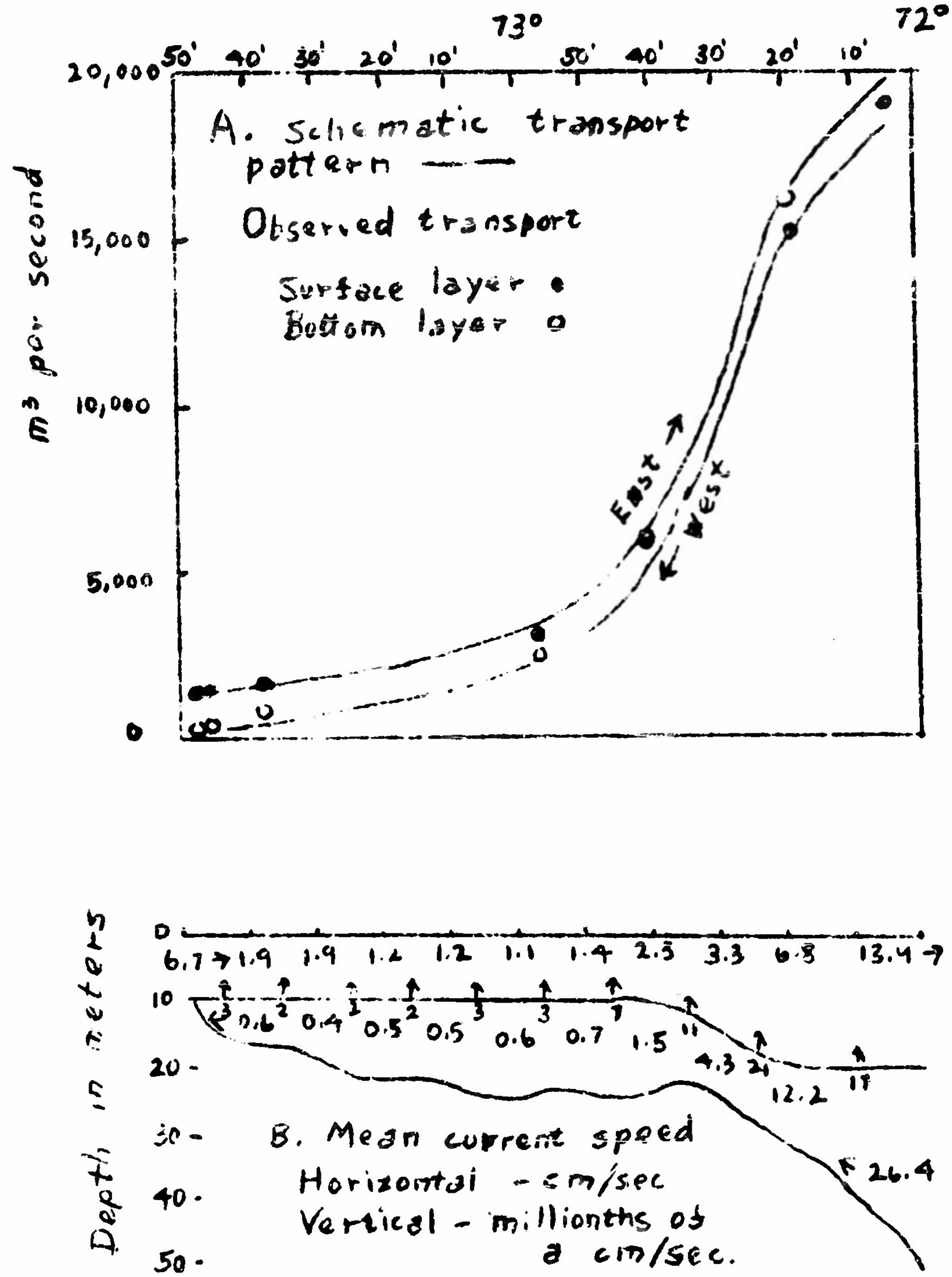
Positive numbers indicate eastward movement, negative are westerly.

Depth Meters	Profile 1	2	3	4	5	6	7
0- 5	680	740	860	2100	4830	7130	9150
5-10	320	540	480	760	750	4870	4830
10-15	100	-130	-240	-70	-1460	2130	4910
15-20			-330	-840	-1380		
20-30				-1390	-2850	-4100	-
30-40						-6840	-
40-50						-4070	-
Total(surface)	1100	1280	1340	2860	5580	14,130	18,890
Total(bottom)	0	-130	-570	-2300	-5690	-15,010	-

augmented by freshwater drainage, amounting to about 300 m^3/second in summer in the whole of Long Island Sound. Hence the net transport at the eastern end of the Sound should be about 1400 m^3/second eastward, but the transport calculations are not accurate enough to demonstrate this.

Figure 3A is a schematic diagram of transport exchange derived from the combination of theoretical considerations and calculated transport. The difference between surface and bottom flow is 1100 m^3/second at the western end of the Sound and gradually increases to 1400 m^3/second in an easterly direction in accordance with the known addition of fresh water. The total exchange increases as a smooth curve that agrees essentially with the calculated transport. Figure 3B converts the transport estimates to horizontal and vertical velocities in the two layers, with due consideration to the principle of mass continuity.

In further studies of the physical and biological oceanography of Long



73°
72°
50'
40'
30'
20'
10'
20,000
15,000
10,000
5,000
0
m³ per second
A. Schematic transport pattern
Observed transport
Surface layer
Bottom layer
East
West
Depth in meters
10
20
30
40
50
6.7
1.9
1.9
1.2
1.2
1.1
1.4
2.5
3.3
6.8
13.4
0.6
0.4
0.5
0.5
0.6
0.7
1.5
4.3
12.2
26.4
B. Mean current speed
Horizontal - cm/sec
Vertical - millionths of a cm/sec.

Figure 3.

Island Sound, we shall be concerned with the effects of transport and diffusion in moving organisms and chemical elements into and out of the Sound and from one part of the Sound to another. In order to justify applying the transport estimates to these problems, it is first necessary to demonstrate that the physical processes as we know them will account for the observed distribution of a conservative property such as salt. We shall proceed then with the construction of a simple mathematical model of salt distribution.

Assume for purposes of simplicity that salt concentrations are uniform in the transverse plane (north-south direction) in Long Island Sound. The transfer of salt may then be regarded as a two-dimensional process occuring along an X-axis directed positively east and a Z-axis directed downward. At any point on this profile the rate of change of salinity S is given by an equation adapted from the general formula for salinity distribution (Sverdrup et al., 1942, p. 159), namely,

$$\frac{\partial S}{\partial t} = \frac{\partial}{\partial x} \cdot \frac{A_x}{\rho} \cdot \frac{\partial S}{\partial x} + \frac{\partial}{\partial z} \cdot \frac{A_z}{\rho} \cdot \frac{\partial S}{\partial z} - V_x \frac{\partial S}{\partial x} - V_z \frac{\partial S}{\partial z} - KS \tag{1}$$

where A_x and A_z are the coefficients of eddy diffusivity on the horizontal and vertical axes, respectively, V_x and V_z are horizontal and vertical velocities, ρ is the density of the water, and K is a coefficient of dilution indicating the rate of addition of freshwater drainage to the water mass.

The velocities V_x and V_z are assumed to be as shown in Figure 3B. ρ is about 1.02 throughout. K is readily estimated as the ratio of freshwater discharge to the volume of the Sound in the area where it enters. Eddy diffusivity depends primarily upon tidal mixing. In a study of estuarine flushing, Arons and Stommel (1951) obtained good results by setting horizontal mixing as a function of the mean tidal velocity and the tidal excursion. Since the latter is the product of the tidal speed and duration, horizontal mixing is essentially proportional to the square of the tidal current. Similarly, Riley (1951) derived a formula applicable to a wide variety of oceanic regions and which will be used in the present example, namely

$$A_x = \frac{(\rho V X)^2}{\mu} \times 6 \times 10^{-12} \qquad (2)$$

where V is the mean tidal current speed, X the distance between points where eddy transfer is measured, and μ is dynamic molecular viscosity. Other formulas in the same paper and calculations of Long Island Sound data indicate that the coefficient of vertical eddy diffusivity in summer is given with sufficient accuracy by

$$A_z = \frac{V}{10} \qquad (3)$$

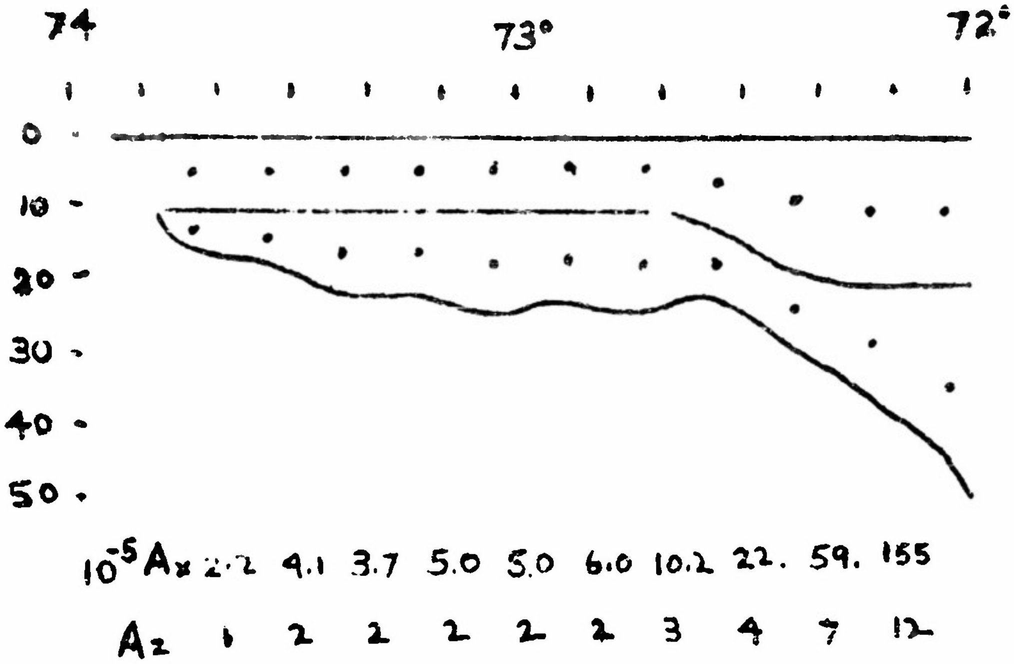
Numerical values are appended to Figure 4A.

The remainder of Figure 4A is the pattern of the mathematical model of salinity distribution. A series of points is laid out at ten-minute intervals of longitude and at the mid-points of the upper and lower strata. At each point it is assumed that the salinity exists in a steady state such that in equation (1) $\partial S/\partial t = 0$. It is further assumed that all of the freshwater drainage is added to the upper layer. Hence in the lower layer $K = 0$.

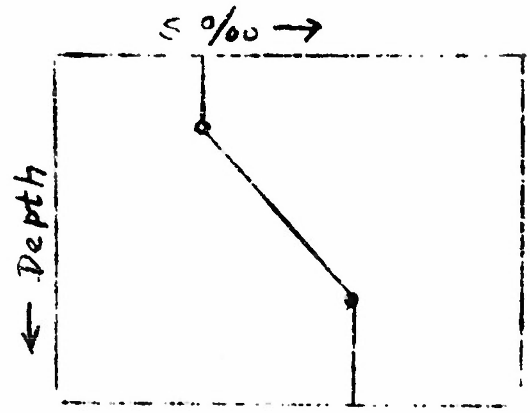
Boundary conditions are defined as follows:

(1) At any point in the pattern the salinity is assumed to be uniform in the upper half of the upper layer and in the lower half of the lower layer. Thus any vertical gradient that exists is between the two points, as illustrated in Figure 4B.

(2) Water entering the pattern at the western end is assumed to have the same salinity as the westernmost point in the pattern.



A. Plan of mathematical model; numerical values for eddy diffusivity ($g\ cm^{-1} sec^{-1}$)



B. Form of salinity gradients postulated for mathematical model.

Figure 4.

(3) Water entering the eastern end at the bottom is arbitrarily assigned a realistic salinity of 31.00 ‰.

As this water of 31 ‰ moves into the Sound it is progressively freshened, and the overall salinity pattern depends upon the quantitative relations of drainage, transport, and diffusion, as defined in equation (1). For purposes of numerical calculation, equation (1) is rewritten in terms of finite differences and in accordance with the specified boundary conditions. Collecting terms, the equation for any point in the upper layer is

$$\begin{aligned} & S_0\left(-\frac{A_x}{\rho x^2} - \frac{A_{-x}}{\rho x^2} - \frac{A_z}{\rho z^2} + \frac{V_x}{2x} - \frac{V_{-x}}{2x} + \frac{V_z}{z}\right) \\ & + S_x\left(\frac{A_x}{\rho x^2} - \frac{V_x}{2x}\right) + S_{-x}\left(\frac{A_{-x}}{\rho x^2} + \frac{V_{-x}}{2x}\right) \\ & + S_z\left(\frac{A_z}{\rho z^2} - \frac{V_z}{z}\right) - KS_0 = 0 \qquad (4) \end{aligned}$$

Designating S_0 as the salinity at any given point, S_x is the salinity at the next point x distance to the east, and the movements of water between the points by diffusion and transport are A_x and V_x, respectively. Similar notation is used for S_{-x}, the salinity at the next point westward, S_z in the bottom stratum, and accompanying physical processes. The equation for a point in the bottom layer is analogous except for omission of the K term.

Since the equation for each point shares terms with the equations for adjacent points, all of the equations in the pattern are related. The whole pattern may therefore be solved by an appropriate method such as the "relaxation" technique of Southwell (1946). The solution is shown in Figure 5A. Observed salinities accompanying the current stations, mainly from Coast and Geodetic Survey data, are shown in the upper part of Figure 5B. The remainder of the figure shows some salinity observations obtained at other times. They reveal a seasonal trend, with the salinity increasing

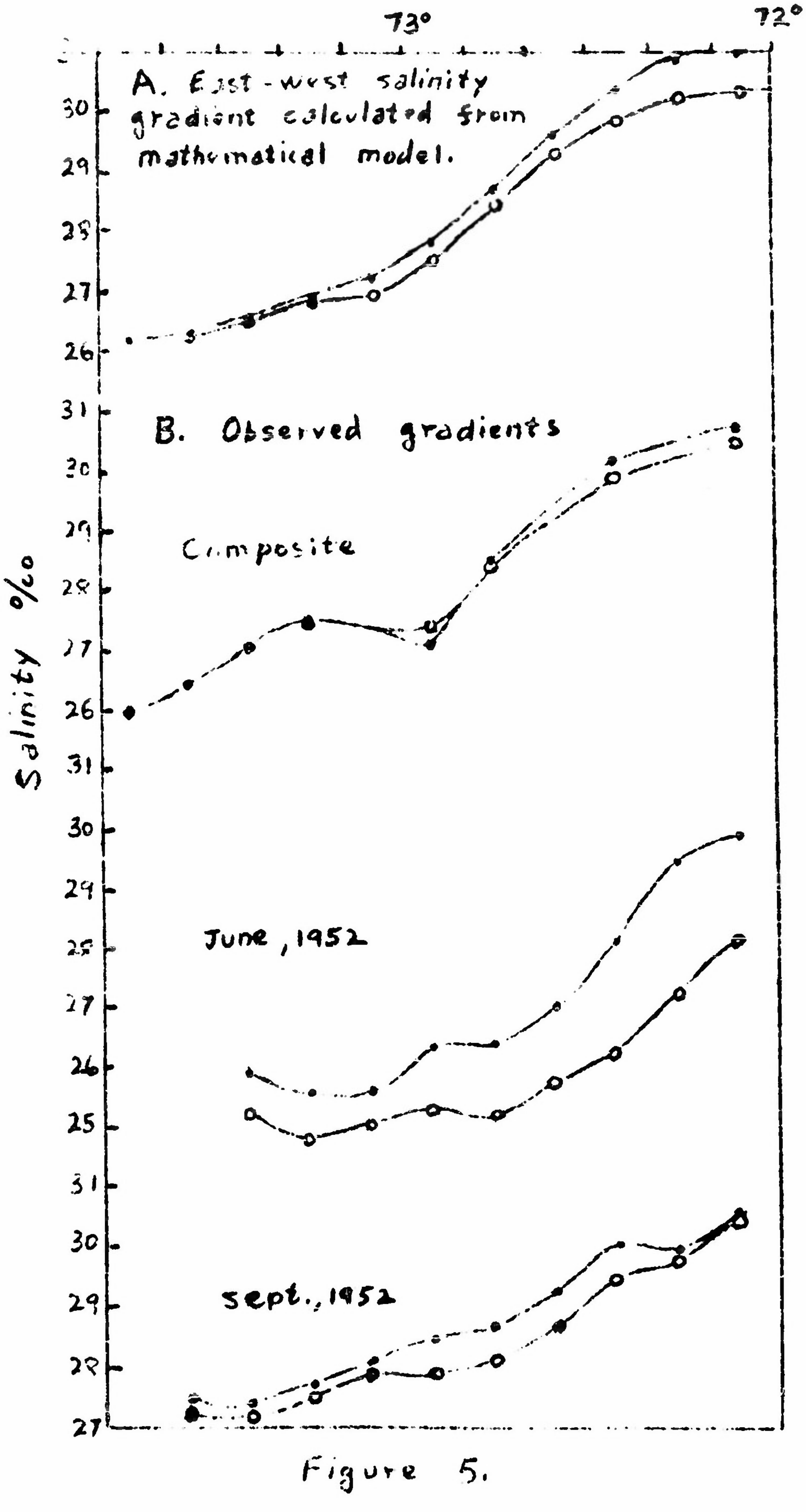

73°
72°
A. East-west salinity gradient calculated from mathematical model.
B. Observed gradients
Composite
June, 1952
Sept., 1952
Salinity ‰
30
29
28
27
26
31
25

Figure 5.

during the summer and the east-west gradient decreasing. In this respect the steady state assumption in the model oversimplifies the problem. Nevertheless, the theoretical curves fall within the limits of observed variation and appear to be representative of average summer conditions. Further expansion of the problem to a consideration of seasonal changes should follow without serious difficulty with the completion of the proposed program for the next two years.

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APPENDIX B. Transparency

We have used two methods to measure the transparency of Long Island Sound waters. The first is the so-called Secchi disc measurement, in which a 20 cm white disc is lowered into the water, and its depth of disappearance is recorded. This crude and old-fashioned method is surprisingly accurate. Some thirty years ago, when Atkins and Poole were developing photoelectric methods for measuring the transparency of English Channel waters, they reported that the photometrically determined extinction coefficients for the visible range of light were closely correlated with Sechhi disc readings, the relation being

$$K = \frac{1.7}{D} \qquad (5)$$

where K is the extinction coefficient per meter and D is the Secchi disc reading in meters. Further comparisons, both in turbid coastal waters and highly transparent oceanic regions have demonstrated that equation (5) is applicable within reasonable limits of error to a wide variety of conditions.

Our second measurement is a photoelectric determination of the extinction coefficient of red light (using a Klett 66 filter) in each water sample. This is determined with reference to a distilled water blank and hence represents total extinction minus the absorption coefficient of distilled water. The primary purpose is to obtain a correction factor for turbidity in colorimetric determinations of phosphate. However, the measurements are also useful for estimating changes in transparency with depth and for evaluating the reliability of the Secchi disc method.

Statistical comparison of some 340 surface water extinction coefficients with the corresponding Secchi disc readings shows a correlation of .74 and yields the equation

$$K = .96\,(K_1 + .255) \qquad (6)$$

where K is derived from the Secchi disc depth according to equation (5) and K_1 is the extinction coefficient for red light, as determined above. The statistically derived constant, .255, which has the fundamental meaning of an absorption coefficient of pure water, is approximately correct for the wave lengths transmitted by the red filter.

It has been recognized for many years that light extinction in sea water is a complex process including absorption by the water and dissolved solids and a combination of absorption and scattering by a variety of suspensoids. The latter include plankton, planktogenic detritus, and - particularly near land - bottom sediments in suspension and particles of terrestrial origin.

In Long Island Sound all of these factors are expected to be operative. In waters of this type, no one has yet succeeded in formulating a quantitative expression for the various influences that govern transparency. We have now amassed sufficient data to attempt such an analysis.

First to be considered is the general problem of absorption and scattering of light by plankton. Rodhe (1948) and others have measured the extinction coefficients of pure algal cultures. In any particular species there was a nearly linear relationship between light ectinction and the number of cells or the chlorophyll concentration. Clarke (1946) compared phytoplankton pigment measurements on Georges Bank with Secchi disc estimates of transparency and demonstrated a crude but significant relationship between them. In an attempt to refine this comparison Figure 6 presents a group of data that is believed to represent the relation in its simplest possible form, namely (a) observations during the spring flowering on Georges Bank, a period when a rapid reduction in transparency coincided with the increase in phytoplankton, and (b) all available oceanic

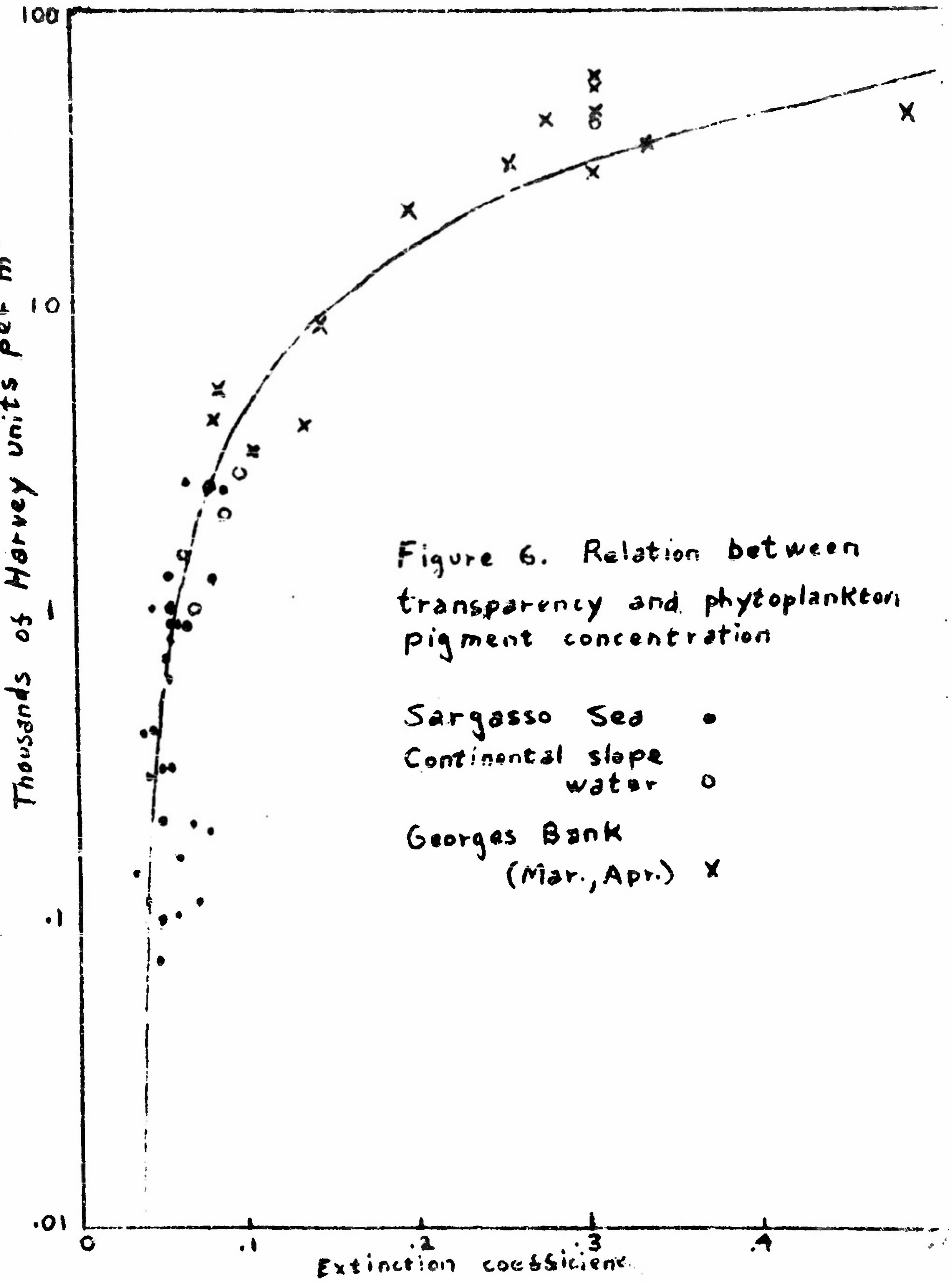

Figure 6. Relation between transparency and phytoplankton pigment concentration

observations, where it may be presumed that particulate matter of non-plankton origin is minimal. Phytoplankton concentrations are expressed as Harvey units of plant pigments per m^3, a type of measurement discussed in the third semiannual progress report. The extinction coefficients were determined photometrically in a few cases, but most of the values are derived from Secchi disc readings according to equation (5).

The relationship revealed by Figure 6 is statistically significant but nonlinear. The 1:1 relation between plant concentration and extinction, which was noted in cultures, seems to be lacking in the sea. A ten-fold increase in pigments produces, at most, a four-fold decrease in transparency.

Three main phenomena are involved in the extinction of light in the cultures and in open oceanic waters. First is the absorption by the water itself. This varies with wave-length. The average is about .04 for the visible part of the spectrum, and the curve in Figure 6 is drawn to the base line at that point. Second, there is absorption by phytoplankton and third, scattering of light by these organisms. In pure cultures both scattering and absorption are expected to be proportional to the cell number, so that the results approximate Beer's law, although the process is much more complicated than in the case of materials in solution.

In a mixed phytoplankton population containing cells of various shapes, sizes, and optical properties, these relationships are seriously altered. The pigment concentration is roughly correlated with the volume of cell material and therefore might be expected to serve as an index of absorption. The details of the scattering process are not understood, but it probably is a function primarily of the area of the cells rather than their total volume.

These are sufficient reasons for the relationship between phytoplankton and extinction coefficients to be much less precise in the sea than in pure laboratory cultures. The explanation of the non-linear tendency in Figure 6 is not so obvious. However, it seems to be true, as a broad generalization, that small species are more nearly constant in number than large ones; the latter dominate the flowerings but are of little significance when the total population is small. Thus the ratio of total area to total volume tends to decrease as the total population increases. Whether or not this is a satisfactory explanation of the observations will require further investigation. Whatever may be the full explanation, Figure 6 presents a relatively precise relationship between plant pigments and transparency, and thus it provides an entering wedge for the investigation of the more complex situation found in coastal waters. The curve used to fit the data has the simple form

$$K = .04 + 2 \times 10^{-6} P + 2 \times 10^{-4} P^{2/3} \tag{7}$$

where K is the extinction coefficient and P is Harvey units of plant pigments per m^3.

Most of the recent observations in Long Island Sound have been measurements of chlorophyll rather than total plant pigments. By applying an average conversion factor, equation (7) is translated to

$$K = .04 + .008R\,C + .054\,C^{2/3} \tag{8}$$

where C is μg of chlorophyll a per liter.

Observed values of K have ranged from 0.25 to 2.0, except during red tides in New Haven Harbor, where a maximum of 5.5 was obtained. Application of equation (8) indicates that phytoplankton accounts for most of the observed variability; however, the calculated extinction coefficients are always too low. The difference between observed coefficients and values obtained from equation (8) averages 0.37, with a standard deviation of $\pm$ 0.23. It seems likely that some or most of this additional absorption and scattering is due to the presence of silt and suspended bottom materials. If so, there should be a correlation with winds, depth of water, and other factors that affect the suspension and settling rates of such materials. Analysis of the data reveals three statistically significant variables which are incorporated in the equation

$$K = .0088\,C + .054\,C^{2/3} + .08\,W - .0074\,d - .077\,S \qquad (9)$$

where W is the average wind in miles per hour during the month when the observation was obtained, d is the depth of water at the station, and S is an expression of vertical stability as indicated by the increase in density between surface and bottom. The relation between observed and calculated values is shown in Figure 7.

The equation accounts for major variations in transparency in Long Island Sound, although considerable error remains. Two-thirds of the calculated K's are within 20% of the observed values. Most of the variation appears to be random, but there is also a small, systematic seasonal error. In the spring the water is more transparent than is indicated by the equation; in summer it is less transparent. None of the physical data available will account for these anomalies. Possibly they indicate that chlorophyll is not fully satisfactory as an indicator of the effect of phytoplankton on transparency, especially since we have found that the ratio of dry weight to chlorophyll in the phytoplankton is relatively low in spring and high in summer.

References cited:

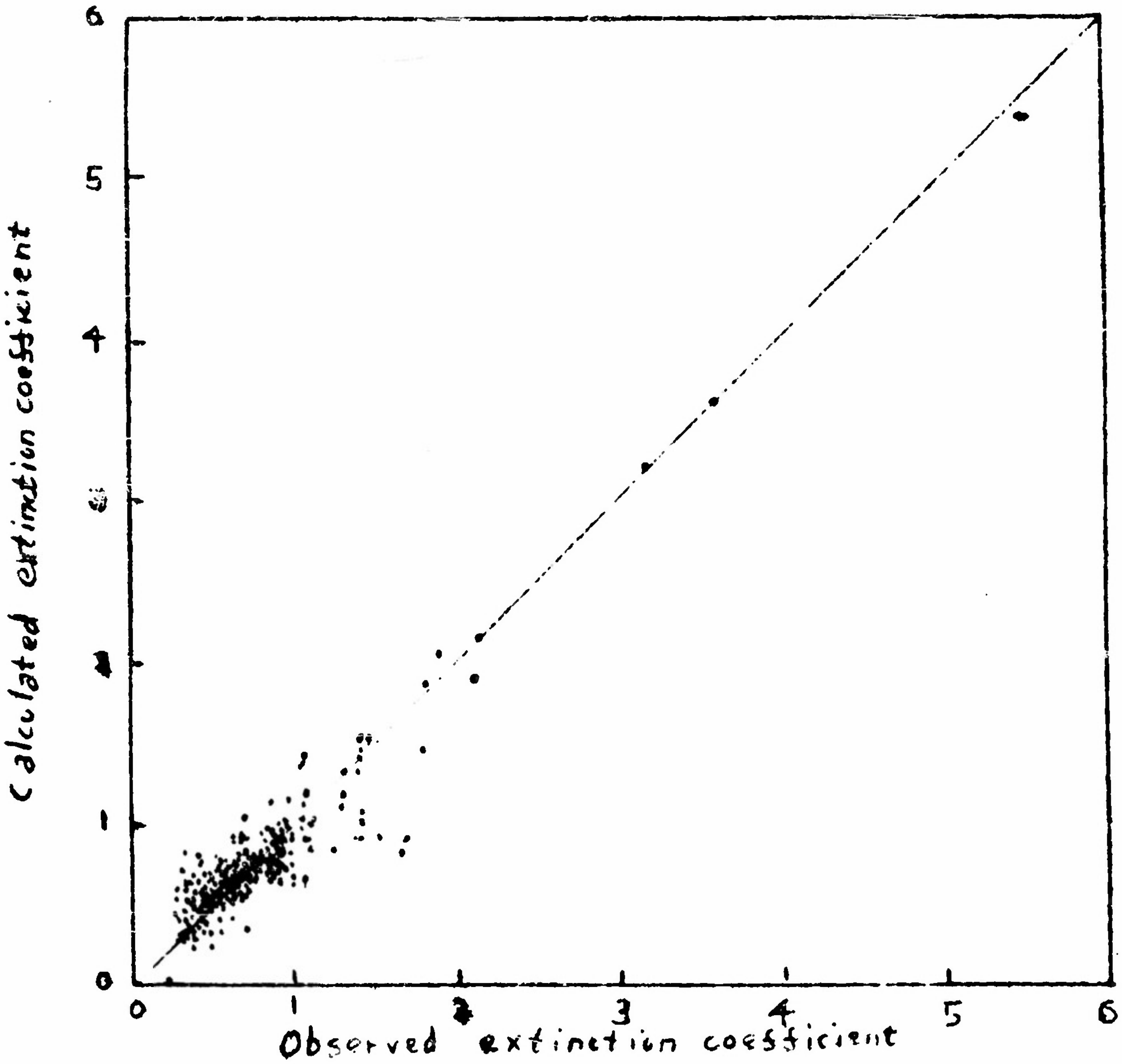

Figure 7. Calculated (equation 9) vs. observed transparency.

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